

APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

LINEARIZING LINC AMPLIFIERS USING PRE-DISTORTION

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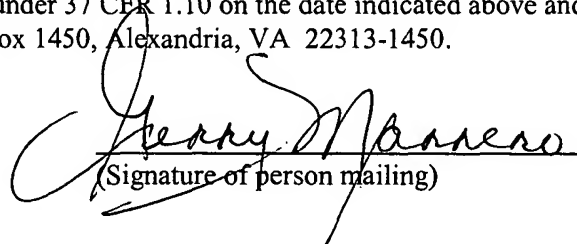
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Cross-Reference to Related Applications

This application claims the benefit of the filing date of U.S. provisional application no. 60/402,168, filed on 08/09/02 as attorney docket no. 1052.013.

Field of the Invention

The present invention relates to signal processing, and, in particular, to techniques for linearizing amplifiers used in communications systems.

Background of the Invention

Both high efficiencies and high linearities can be achieved in RF amplifiers using a set of techniques known as amplitude reconstruction. In amplitude reconstruction, the amplitude information of a signal is removed, and the remaining phase-modulated signal is amplified using a highly efficient nonlinear amplifier. After amplification, the amplitude information is somehow returned to the signal.

One such technique for amplitude reconstruction is LINC (LInear amplification with Nonlinear Components), also referred to in older literature as outphasing. In this technique, the amplitude information in the signal is converted into phase modulation for two different signals. The phase modulation is performed in such a manner that when the two signals are amplified and then recombined, the resulting signal has the desired output amplitude. If the input signal has zero amplitude, then the two amplified signals will be 180 degrees out-of-phase and will cancel when recombined. If the input signal is at maximum amplitude, then the two amplified signals will be in-phase and will combine perfectly.

Fig. 1 is a block diagram of a LINC system 100 of the prior art. LINC system 100 comprises LINC modulator 102, power amplifiers PA1 and PA2, and combiner 104. The input signal to LINC system 100 is an amplitude-modulated carrier represented as $A \sin(\omega t + \phi)$. LINC modulator 102 generates two signals with phases $\phi + \cos^{-1}(A)$ and $\phi - \cos^{-1}(A)$. These two signals are then amplified by amplifiers PA1 and PA2, respectively, and combined by combiner 104 to produce an amplified replica of the input signal. Peak output is obtained when the two amplifiers add in-phase; zero output is obtained when they add out-of-phase. Intermediate phase values produce intermediate amplitudes.

In phasor notation, the input signal may be written as in Equation (1) as follows:

$$u = Ae^{j\phi}. \quad (1)$$

The outputs of amplifiers PA1 and PA2 may be written as in Equations (2) and (3) as follows:

$$V_1 = Ge^{+j(\phi - \cos^{-1} A)} \quad (2)$$

and

$$V_2 = Ge^{+j(\phi + \cos^{-1} A)}, \quad (3)$$

where G is the gain of both power amplifier PA1 and power amplifier PA2. The output y of combiner 104 may be written as in Equation (4) as follows:

$$y = 2GAe^{j\phi}. \quad (4)$$

There are two common methods for combining the two amplified signals generated by amplifiers PA1 and PA2. These two methods are described below in the context of Figs. 2 and 3.

Fig. 2 shows a block diagram of a LINC system 200 of the prior art that employs a first method for combining the amplified signals generated by two power amplifiers. LINC system 200 has a LINC modulator and two power amplifiers that are analogous to those in LINC system 100 of Fig. 1. In LINC system 200, combiner 104 of Fig. 1 is implemented using a four-port hybrid combiner 204, also known as a power combiner. Combiner 204 receives the amplified signals from amplifiers PA1 and PA2 as two inputs and generates the sum and difference of the two signals as its two outputs. The sum is an amplified version of the input signal to the LINC system, while the difference signal is wasted in a dummy load. The advantage to such a technique is that each amplifier sees a perfectly matched load. However, some power is wasted in the dummy load, resulting in a loss of efficiency. (Note that, at zero input amplitude, all power is wasted in the difference port.)

Fig. 3 shows a block diagram of a LINC system 300 of the prior art that employs a second method for combining the amplified signals generated by two power amplifiers. Like LINC system 200, LINC system 300 has a LINC modulator and two power amplifiers that are analogous to those in LINC system 100 of Fig. 1. In LINC system 300, combiner 104 of Fig. 1 is implemented using a three-port, lossless combiner 304. Combiner 304 is implemented using a transmission line tee 306 with transmission line stubs (e.g., shunt reactances) 308 and 310 for impedance matching. Alternatively, combiner 304 may be implemented using a transformer. In either case, this LINC system has the advantage of efficiency over the four-port hybrid technique of LINC system 200, since no power is lost in the combiner. Unfortunately, the amplifiers no longer see perfectly matched loads at all output amplitudes. As a result, while the combiner itself is extremely efficient, most amplifiers that are used in

such systems lose efficiency when connected to mismatched loads. In addition, their power outputs and phases may vary with the output amplitude of the system.

LINC system 300 uses shunt reactances (jB_s and $-jB_s$ in Fig. 3) to improve the efficiency of a basic three-port system to improve amplifier matching at output amplitudes other than the maximum amplitude. In particular, shunts 308 and 310 are preferably placed at the electrical equivalent of one-quarter wavelength away (e.g., via quarter-wave delays 312 and 314) from combiner tee 306, where the shunts improve the load matching at a variety of output amplitudes. This greatly increases efficiency and linearity at some output amplitudes at the expense of some efficiency and linearity in other amplitudes. The optimum compensation depends heavily on the peak-to-average ratio of the signal to be amplified.

Brief Description of the Drawings

Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which like reference numerals identify similar or identical elements.

Fig. 1 is a block diagram of a LINC system of the prior art;

Fig. 2 shows a block diagram of a LINC system of the prior art that employs a first method for combining the amplified signals generated by two power amplifiers;

Fig. 3 shows a block diagram of a LINC system of the prior art that employs a second method for combining the amplified signals generated by two power amplifiers;

Fig. 4 shows a block diagram of a LINC system, according to one embodiment of the present invention; and

Fig. 5 shows a possible implementation of the pre-distorter and LINC modulator of the LINC system of Fig. 4, in which the pre-distortion and LINC modulation functions are performed by a single set of combined circuitry.

Detailed Description

Despite the efficiency benefits of LINC systems using four-port hybrid combiners or three-port lossless combiners, LINC systems are typically not linear enough for use with many modern signals. In the case of the four-port hybrid combiner of Fig. 2, a small difference in the gain or phase offsets of each amplifier will result in different powers going into the combiner. As a result, the phase component of one signal will dominate over the other, which will result in distortion at the output signal.

In the LINC system of Fig. 3, load matching is significantly improved, but is still not perfect. The changing gains of the amplifiers at various load conditions will cause both gain distortion (amplitude

modulation to amplitude modulation or AM-AM distortion) and phase distortion (amplitude modulation to phase modulation or AM-PM distortion). According to embodiments of the present invention, the LINC system of Fig. 3 is linearized by pre-distorting the input signal in a manner that compensates for the distortion of the LINC system, which is usually measurable and consistent.

Fig. 4 shows a block diagram of a LINC system **400**, according to one embodiment of the present invention. LINC system **400** has pre-distorter **401**, LINC modulator **402**, power amplifiers PA1 and PA2, and combiner **404**. In preferred implementations, power amplifiers PA1 and PA2 and combiner **404** are analogous to the power amplifiers and combiner of Fig. 3, where combiner **404** may be implemented as a transformer (as represented in Fig. 4) or as a transmission line tee with transmission line stubs for impedance matching (as represented in Fig. 3).

In one possible implementation, pre-distorter **401** and LINC modulator **402** are implemented using distinct circuitry, where LINC modulator **402** is analogous to the LINC modulator of Fig. 3 and pre-distorter **401** may be any suitable type of pre-distorter as is known in the art. In this case, LINC modulator **402** receives and processes the pre-distorted signal from pre-distorter **401** as its input.

In phasor notation, for the input signal of Equation (1), the output of pre-distorter **401** may be represented as in Equation (5) as follows:

$$u = g(A)e^{j(\phi+p(A))} , \quad (5)$$

where $g(A)$ is the amplitude-dependent gain adjustment and $p(A)$ is the amplitude-dependent phase adjustment of the of the pre-distortion processing. When this pre-distorted signal is applied to LINC modulator **402**, the two LINC-modulated, pre-distorted outputs x_1 and x_2 may be represented as in Equations (6) and (7) as follows:

$$x_1 = e^{+j(\phi+p(A)-\cos^{-1}g(A))} \quad (6)$$

and

$$x_2 = e^{+j(\phi+p(A)+\cos^{-1}g(A))} . \quad (7)$$

Fig. 5 shows a block diagram of a combined implementation of pre-distorter **401** and LINC modulator **402** of LINC system **400** of Fig. 4, according to an alternative embodiment of the present invention. According to this embodiment, the pre-distortion and LINC modulation functions are performed by a single set of combined circuitry **500**.

In particular, combined pre-distortion/LINC modulation circuitry **500** comprises phase detector **502**, envelope detector **504**, look-up tables (LUTs) **506** and **508**, difference node **510**, summation nodes

512-516, and modulators 518-520. Phase detector 502 detects the phase of the input signal and applies the detected phase ϕ to summation nodes 514 and 516. Envelope detector 504 detects the amplitude of the input signal and applies the detected amplitude A to LUTs 506 and 508, which use the detected amplitude as an index into their respective stored data.

Each LUT is loaded with information based on the known distortion properties of the system. Such tables can be used to automatically correct for the gain and phase distortions of the amplifier. In particular, LUT 506 maps amplitude A to the amplitude-dependent, pre-distortion phase adjustment term $p(A)$, while LUT 508 maps amplitude A to the amplitude-dependent, LINC modulation phase offset term $\cos^{-1}(g(A))$. Both of these LUT values are applied to difference node 510 and summation node 512.

Difference node 510 generates the difference between the two LUT values and applies the resulting difference to summation node 514. Summation node 512 generates the sum of the two LUT values and applies the resulting summation to summation node 516. The outputs of summation nodes 514 and 516 are applied to modulators 518 and 520, respectively.

Each modulator modulates its received summation signal at the carrier frequency ω . As such, modulator 518 generates the LINC-modulated, pre-distorted output signal x_1 whose phasor representation is given by Equation (6), while modulator 520 generates the LINC-modulated, pre-distorted output signal x_2 whose phasor representation is given by Equation (7). The output signals x_1 and x_2 from modulators 518 and 520 are applied to power amplifiers PA1 and PA2, respectively, of LINC system 400 of Fig. 4.

If appropriate, the output signals can be monitored and the lookup tables adjusted for changes in the distortion properties of the system during operation.

Although combined circuitry 500 of Fig. 5 adds and subtracts different signals in a particular sequence, it will be understood that the present invention can alternatively be implemented using other sequences of addition and subtraction nodes that generate equivalent results.

The present invention may be implemented in the context of wireless signals transmitted from a base station to one or more mobile units of a wireless communication network. In theory, embodiments of the present invention could be implemented for wireless signals transmitted from a mobile unit to one or more base stations. The present invention can also be implemented in the context of other wireless and even wired communication networks to reduce spurious emissions.

Embodiments of the present invention may be implemented as circuit-based processes, including possible implementation on a single integrated circuit. As would be apparent to one skilled in the art, various functions of circuit elements may also be implemented as processing steps in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.

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It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims.